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# SUBNANOSECOND TIME RESOLUTION SINGLE-CHANNEL PULSE-HEIGHT ANALYZER

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## SUMMARY

A fast single-channel pulse-height analyzer is described that employs a unique tunnel diode trigger circuit to generate accurately timed output pulses. The analyzer described herein was developed for use in nanosecond nuclear physics coincidence and lifetime studies and will handle approximately $10^4$ random pulses per second above the lower discriminator level with negligible output pulse loss.

With the radioactive isotope cobalt 60, which produces an essentially simultaneous ($<10^{-12}$ sec) two-gamma-ray cascade, two gamma-ray detectors consisting of plastic scintillator and photomultiplier tube, and two fast single-channel pulse-height analyzers, a resolution curve of 0.57-nanosecond full width at half maximum height was obtained when the upper 25 percent of the cobalt 60 gamma-ray pulse-height spectrum produced in each of the gamma-ray detectors was used.

## INTRODUCTION

The application of very fast electronic devices to nuclear particle detection systems has made possible the measurement of nuclear state lifetimes shorter than 1 nanosecond. The particle detection system used for this purpose consists of (a) a scintillator in which the energetic particle produces a light flash, (b) a photomultiplier tube that generates an electrical pulse from each light flash, and (c) some sort of pulse discriminator that responds to sufficiently large input pulses by producing an output pulse large enough to operate some form of time measuring device. This discriminator device will be of chief concern herein. In nuclear lifetime measurements, two such detector systems are required. One signals the formation of the short-lived state (by detection of the particle emission leading to this state), and the second signals the disappearance of the state (by

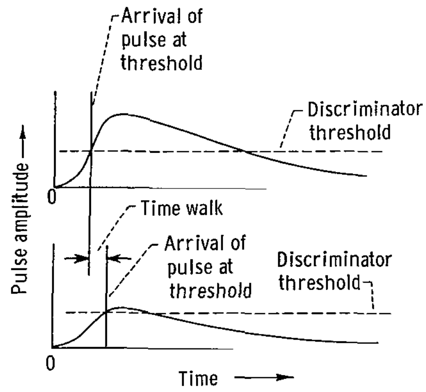



Figure 1. - Origin of "time walk."

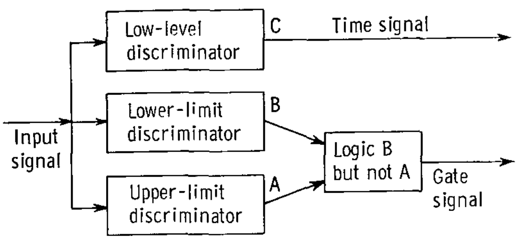



Figure 2. - Conventional antiwalk system.

detection of a particle produced in the disappearance of the state). If extremely short lifetimes are to be measured, each detector must exhibit in the time dimension a nearly unique response to the triggering event.

Gatti and Svelto (ref. 1) have examined the theoretical timing ability of a detection system in terms of the statistical nature of the scintillator decay and the photomultiplier response. Their investigation showed that the best timing for monoenergetic pulses would be obtained if current pulses from the photomultiplier tube were integrated and allowed to trigger the discriminator when they reached approximately 0.2 of their ultimate value. Unfortunately, the detected particles do not commonly produce a monoenergetic pulse in the scintillator-photomultiplier system but rather a whole spectrum of pulse sizes. In this situation the criterion of reference 1 cannot be met, and the time response of the discriminator displays "time walk," which is discussed in some detail in reference 2.

In essence, time walk occurs because pulses of differing size reach the discriminator trigger threshold at slightly different times after their initiation. The orgin of time walk is shown in figure 1. The amount of time walk for a simple discriminator will be somewhat less than the rise time of the pulses presented to it. In order to minimize timing uncertainties due to time walk, a three-discriminator system (fig. 2) is commonly employed. In this system discriminators A and B together with the anticoincidence logic circuit form a single-channel pulse-height analyzer that provides an output pulse whenever an input pulse lying in the narrow range between the A and B discriminator thresholds is received. This analyzer output is used to gate the time measurements obtained from discriminator C signals so that these results are, in effect, obtained from nearly monoenergetic pulses.

A second cause of timing error is due to the fact that events associated with nuclear transformations occur randomly in time. As a consequence of this randomness, a fraction of the pulses will arrive at the discriminator while it is still recovering from the preceding pulse. Since the effective threshold level of a discriminator varies during this recovery period, a "time jitter" is produced just as varying pulse size introduces time walk with a fixed threshold. This time jitter is therefore still a problem in the system

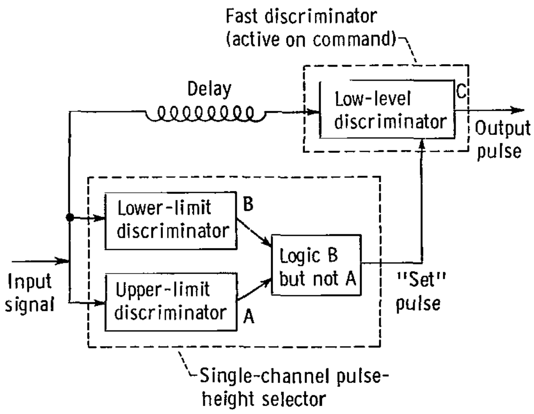


Figure 3. - Signal logic of fast single-channel pulse-height analyzer.

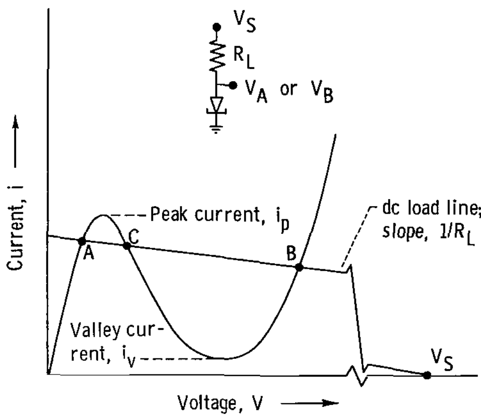


Figure 4. - Tunnel diode current-voltage characteristics with two stable operating voltages for direct-current load line shown.

of figure 2, but it may be eliminated by introducing a blanking circuit (ref. 3), which gates the measuring-recording unit off whenever the C discriminator output signal (fig. 2) has been preceded by an earlier pulse within a fixed time interval. In summary then, the detection systems commonly employed in extremely short lifetime measurements contain a sensitive fast discriminator that produces a timing signal pulse for nearly all the events occurring. Time walk and jitter are then eliminated by employing suitable auxiliary discriminators and logic circuits to select only a small fraction of these pulses that are relatively free of time uncertainties.

At the Lewis Research Center subnanosecond lifetime measurements have been of concern in connection with positron annihilation studies. It was felt that if the preceding logic were reversed, that is, if the logic B but not A shown in figure 2 were first performed and then the gate signal were used to activate a normally passive low-level discriminator, an improved and much less cumbersome detection system could be obtained. A system embodying the logic reversal and a discriminator of this type is described.

## CIRCUIT DESCRIPTION

Figure 3 shows the fast single-channel pulse-height analyzer in capsule form and can be compared with figure 2. The logic is now perhaps more apparent. Input pulses are selected by the single-channel pulse-height selector. The chosen pulses produce a setting action in the fast discriminator circuit, which then generates an output pulse upon receiving the delayed input signal. The single-channel analyzer reduces time walk as previously explained, while time jitter is all but eliminated by allowing the fast discriminator to generate outputs on command only. The operation of the fast discriminator relies on the facts that tunnel diodes may be operated as bistable devices if they are supplied from a constant current source and may be switched from one state to the other very rapidly if current pulses of the correct magnitude are injected. In figure 4 the

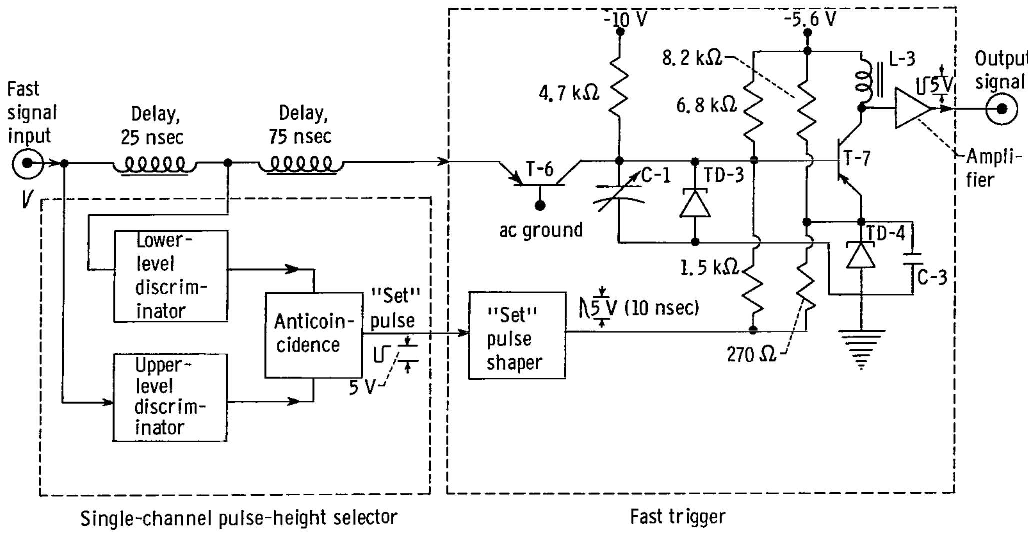



Figure 5. - Block diagram of analyzer showing important components of fast discriminator in detail.

current-voltage characteristics of a tunnel diode are shown along with the direct-current load line for the resistor - tunnel-diode circuit shown. The two stable states are the low-voltage or "off" state A and the high-voltage or "on" state B. Point C is not a stable operating point because of the negative conductance of the tunnel diode in this region. Current pulses of the correct magnitude and polarity can cause the tunnel diode to change from one state to the other.

Figure 5 shows the major components of the fast-discriminator circuit in more detail. Its major components are tunnel diodes TD-3 and TD-4, transistor T-7, and capacitor C-3. Transistor T-7 is so arranged that it will conduct only when TD-3 but not TD-4 is in the high-voltage state (i.e., position B, fig. 4). The voltage difference between B and A is sufficient to cause germanium transistors to conduct strongly. The sequence of events that leads to this condition is as follows: With TD-3 and TD-4 both in their on state, a positive "set" pulse forces TD-3 and then TD-4 (after C-3 discharges) into their low-voltage state. Tunnel diodes TD-3 and TD-4 are initially held in their on state by current flow through the 6.8- and the 8.2-kilohm resistors. These resistors are large enough to provide less than tunnel diode peak current $i_p$ (see fig. 4) but more than valley current $i_v$. Both tunnel diodes will therefore remain in their off state until a negative pulse is received. A fast input pulse produces a limiting action in transistor T-6. The negative current pulse at its collector turns on TD-3. When TD-3 is turned on, T-7 conducts until C-3 builds up sufficient charge to cause TD-4 to turn on again, at which time T-7 ceases to conduct. A second pulse entering the limiter can produce no further action because TD-3 and TD-4 are already on and will remain so until another set pulse is received. The voltage pulse appearing at the collector of T-7 is amplified and limited and becomes the analyzer output. The insertion of variable

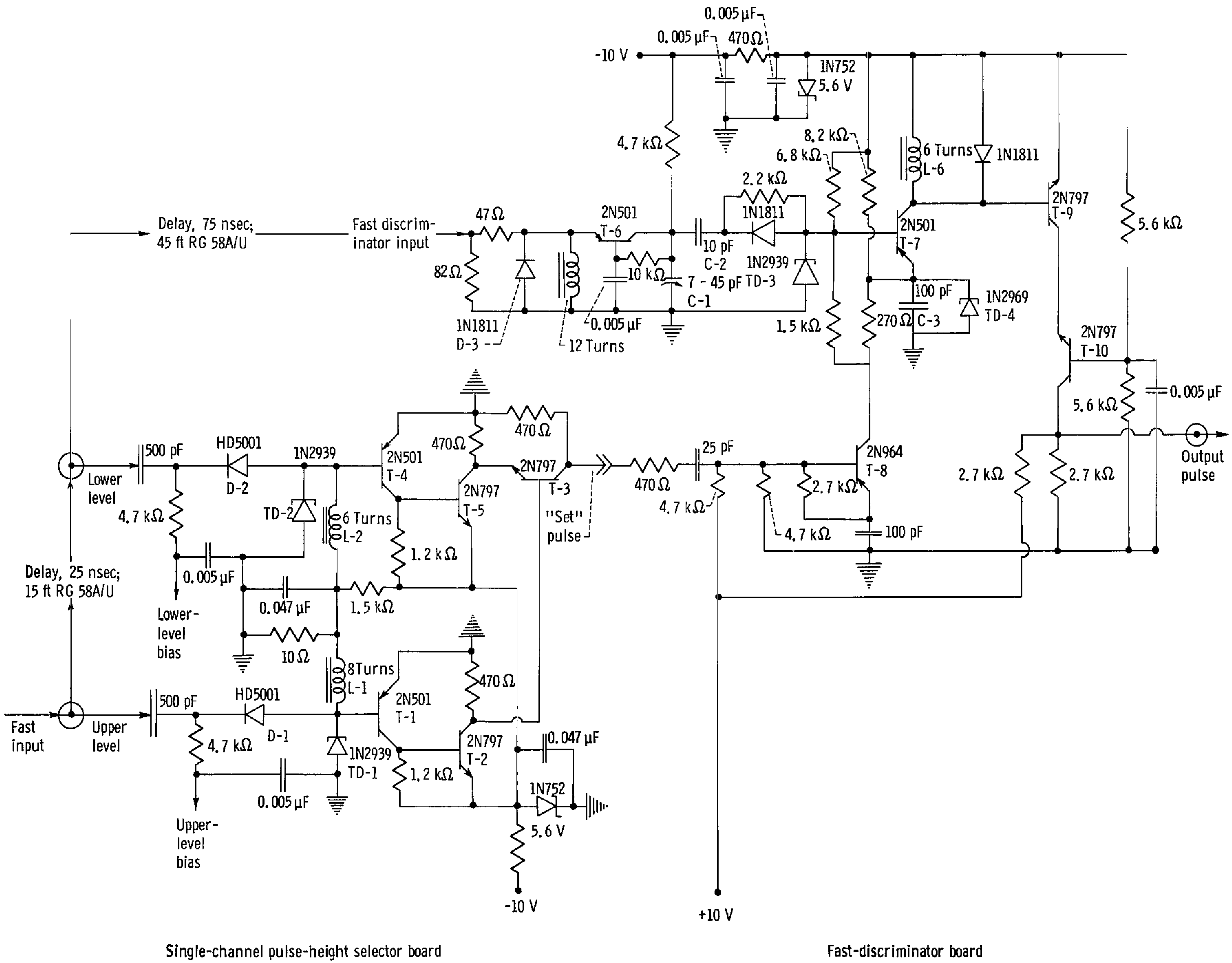



Figure 6. - Complete circuit diagram of analyzer. Inductances formed by winding no. 28 wire on ferrite cores.

capacitor C-1 between the collector and the ground of T-6 decreased the time walk of the circuit.

The circuit diagram of the complete fast single-channel pulse-height analyzer is shown in figure 6. Fast input signals that produce minimum time walk are selected by the moderately fast single-channel pulse-height selector consisting of upper- and lower-level tunnel-diode univibrator discriminators and an anticoincidence circuit. The upper-level discriminator consists of diode D-1, tunnel diode TD-1, inductance L-1, and transistors T-1 and T-2, and the lower-level discriminator consists of D-2, TD-2, L-2, T-4, and T-5. The upper- and the lower-level biases allow for discrimination of the fast input pulse. Transistor T-3 is the anticoincidence element. Producing single-channel selector action involves the application of the output of the lower-level discriminator to the T-3 emitter and the connection of the output of the upper-level discriminator to its base. In the absence of an upper-level discriminator pulse, T-3 acts as a common base amplifier and produces a set pulse at its collector. If an upper-level pulse exists, T-3 is cut off and no set pulse is produced. In order to ensure anticoincidence action, the upper-level discriminator pulse is approximately 200 nanoseconds long and precedes the lower-level pulse, which is 125 nanoseconds long, by approximately 25 nanoseconds. The delay is produced by the insertion of 15 feet of RG 58A/U coaxial cable between the upper- and the lower-discriminator inputs. The output of the anticoincidence circuit (the set pulse) is shaped in transistor T-8 and produces a short positive set pulse at its collector. This pulse sets TD-3 and TD-4 to their low-voltage state by current flow in the 1500- and the 270-ohm resistors. The fast input signal, which is delayed a total of 100 nanoseconds, is terminated at the emitter of T-6 by the parallel-series combination of diode D-3 and the 82- and 47-ohm resistors. This delay is introduced to ensure that electrical quiescence exists in the fast-discriminator circuit after it has received a set pulse. The limited pulse produced at the collector of T-6 is differentiated in C-2, and the resulting current pulse switches TD-3 to its on state. The on voltage of TD-3 causes T-7 to conduct strongly until C-3 reaches the TD-4 firing voltage, at which time T-7 ceases to conduct. Any further pulse presented to TD-3 before another set pulse has been received cannot develop sufficient voltage in TD-3 (because of the high conductance of the tunnel diode in the on state) to cause further conduction in T-7. The pulse produced at the collector of T-7 is amplified and limited in T-9 and T-10 and produces a relatively uniformly shaped 5-volt negative pulse, the leading edge of which is well related in time to the fast input signal. The output pulse is approximately 120 nanoseconds long and may be increased to some extent by increasing the value of C-3. Use of the circuit with time-to-pulse height converters of the overlapping type requires some additional shaping of the output pulse. In order to produce the best possible timing, variable capacitor C-1 was adjusted until the fast-discriminator inputs, as observed with a fast oscilloscope gated by the accompanying analyzer outputs, showed the least time walk. The best value for

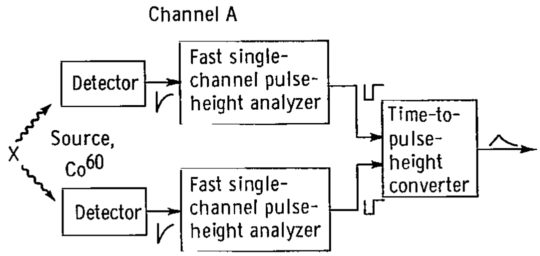


Figure 7. - Block diagram of fast coincidence experiment.

C-1 was approximately 15 picofarads. Capacitor C-1 apparently reduces the effect of the pulse feedthrough of transistor T-6.

The fast single-channel pulse-height analyzer circuitry is constructed on two $2\frac{1}{2}$- by 3-inch terminal boards attached to transistor terminal-board connectors that fit into mating sockets on a plug-in module. Necessary delay lines are enclosed in a 3- by 4- by 5-inch aluminum box also mounted on the module. The upper and lower discriminator biases are controlled by two 5-kilohm potentiometers connected between ground and 3.6 volts. The fast input signals and the analyzer output pulses enter and exit through BNC connectors and along with the discriminator bias controls are mounted on the front of the plug-in module.

## CIRCUIT PERFORMANCE

In order to display the precision with which the analyzer described herein provides a knowledge of the time of occurrence of an input signal, a simple coincidence experiment was performed with the use of the radioactive isotope cobalt 60 ($Co^{60}$). This isotope emits two gamma rays of about equal energy within about $10^{-12}$ second of one another. The expected time walks are at least two orders of magnitude larger than this value, and consequently the two $Co^{60}$ gamma rays may be considered as two simultaneous related (prompt) events. The experimental arrangement necessary for the performance of this measurement is shown in figure 7.

Two nuclear detectors consisting of 2- by 2-inch cylinders of plastic scintillator (Pilot B) optically coupled to photomultiplier tubes (56 AVP) were connected to two fast single-channel pulse-height analyzers with the detectors viewing the $Co^{60}$ source. The analyzer outputs were connected to a time-to-pulse converter similar in design to one described by Grin and Joseph (ref. 4). This converter measures the overlap in time of two pulses presented to it and produces an output voltage pulse proportional in size to the overlap. A calibration of the system by insertion of added known delays permits conversion of this output voltage pulse back to a time measurement. Related gamma rays that produce detector-analyzer outputs should produce constant-size converter output; however, because of the residual analyzer time walk and the scintillator and photomultiplier tube statistics, the resultant output is a distribution about this mean value. The figure of merit used in measurements of this sort is the full width at half maximum height of the time distribution of a large number of prompt events.

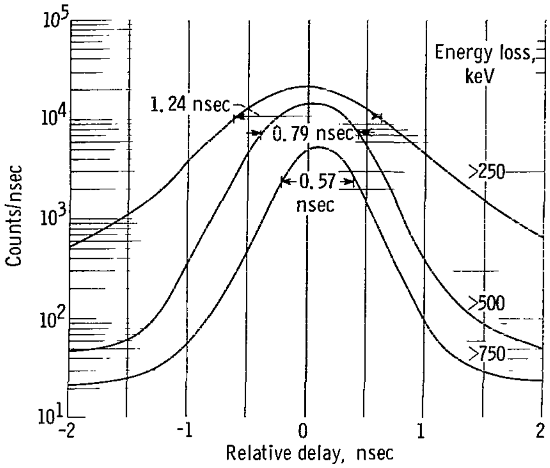
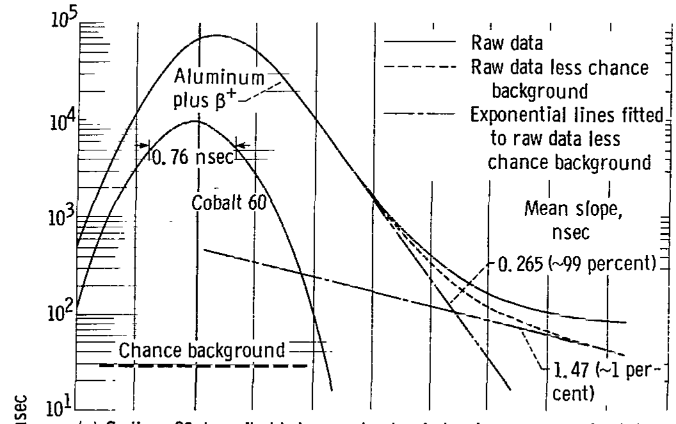
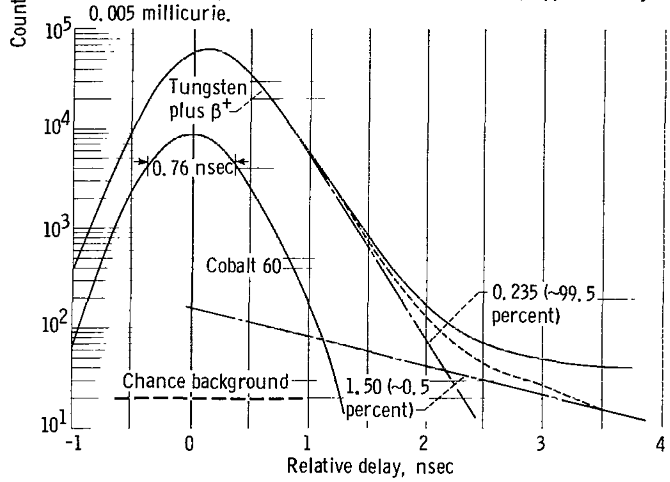



Figure 8. - Resolution curves obtained with cobalt 60 and three different discriminator settings. Counting time for each curve, 30 minutes.




(a) Sodium 22 deposited between sheets of aluminum, approximately 0.005 millicurie.




(b) Sodium 22 deposited between sheets of tungsten, approximately 0.01 millicurie.

Figure 9. - Resolution curves obtained with sodium 22. Prompt curve obtained with cobalt 60 and same energy windows is shown for comparison.

The time distribution obtained from prompt $Co^{60}$ events is shown in figure 8. For the three curves each analyzer was made to accept pulses produced by the $Co^{60}$ in the plastic scintillator corresponding to energy losses greater than 750, 500, or 250 keV and less than 1000 keV. The full widths at half maximum height are 0.57, 0.79, and 1.24 nanoseconds, respectively. These results can be compared with a curve obtained by Schwarzchild (ref. 3), which has a full width at half maximum height of 0.32 nanosecond with pulses lying between approximately 800 and 1000 keV. Smaller detectors and faster scintillators would probably improve the resolution to a comparable point. The effect of smaller scintillators has not been determined as these analyzers were constructed for use in the study of positron lifetimes in condensed gases (refs. 5 and 6), and because of the physical dimensions of the experimental setup large detectors were necessary to ensure respectable counting rates.

In order to demonstrate the results achievable in short lifetime measurements, two time distributions were obtained with the $Co^{60}$ source shown in figure 7 replaced with a source composed of a positron emitter (sodium 22) sandwiched between either aluminum or tungsten sheet. Sodium 22 emits a 1.28-meV gamma ray and a positron simultaneously.

The positron exists either as a free positron or forms a bound state (positronium), both of which are energetically unstable. The mean period of time that a positron can exist in such a configuration depends on the microscopic surroundings. As in all nuclear phenomena, the distribution of individual positron lifetimes from a given state is exponential in character. A measurement of the exponential slope of the time distribution provides a knowledge of the mean life of the state. The disappearance of the positron or the positronium is signaled by the formation of 1.02 meV of gamma-ray energy usually in the form of two 0.511-meV gamma rays.

The results obtained for aluminum and tungsten are shown in figures 9(a) and (b), respectively. In each case a prompt ($Co^{60}$) spectrum is shown for comparison. These curves were obtained by setting channel A (see fig. 7) to detect only the nuclear gamma ray and channel B to detect mainly annihilation gamma rays. Channel A detected pulses corresponding to energy losses greater than 0.64 meV and less than 1.07 meV, while channel B detected those between 0.24 and 0.34 meV. The prompt curves were obtained with these same energy windows. The free positron mean lives in aluminum and in tungsten have been measured by a comparison technique (ref. 9) to be 0.257 and 0.220 nanosecond, respectively. The measured values obtained from the mean experimental slopes of the resolution curves are 0.265 and 0.235 nanosecond for aluminum and tungsten, respectively. Both curves display a long weak component of about equal intensity (1 percent) and mean life (1.5 nsec). These components may be instrumental although long mean life components have been observed in metals (ref. 8.)

As an illustration of the excellent stability of this system, a tungsten - sodium 22 sample was run for 1000 minutes and compared with the results of a 20-minute run. The full width at half maximum height of the resolution curves differed by at most one-half channel or about 0.035 nanosecond.

## CONCLUSIONS

A fast single-channel pulse-height analyzer that can be used in most nuclear physics coincidence applications requiring pulse-height discrimination is described. Four factors make this instrument an attractive system for these applications: It has excellent timing capabilities, is extremely stable, is relatively simple in concept, and replaces a considerable quantity of electrical circuits with one compact plug-in unit.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 7, 1964.

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